

Effects of increased spacing on carbon mineralization rates and temperature in a stand of young balsam fir

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Treatment to reduce density, from 19 000 stems/ha to about 1642 stems/ha at a regular spacing of 2.4×2.4 m, in a young balsam fir (*Abies balsamea* (L.) Mill.) stand stimulated carbon mineralization rates of the litter layer which were, in turn, positively correlated with inorganic nitrogen levels. Increased carbon mineralization rates were attributed to increased summer temperatures in the litter layer. Temperature measurements under the snow indicated a consistently lower winter temperature in the treated stand as compared with the control. The increased and more regular spacing in the treated stand resulted in more rapid basal area growth, increased needle weights, and greater foliar N concentrations, reflecting an increased nitrogen uptake by the trees.

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La réduction du nombre de tiges, de 19 000 à quelque 1642 tiges/ha, à espacement régulier de 2.4×2.4 m dans un jeune peuplement de sapin baumier (*Abies balsamea* (L.) Mill.) a stimulé le taux de minéralisation du carbone organique de la litière et partant augmenté la teneur en azote minéral. La minéralisation accrue de la matière organique est attribuée à l'augmentation des températures estivales dans la couche de litière. Les températures sous la neige se sont avérées plus basses dans le peuplement traité que dans le témoin. L'espacement accru et plus régulier des tiges dans le peuplement traité s'est traduit par un accroissement plus rapide de la surface terrière, une augmentation de la masse des aiguilles et de la concentration en azote foliaire, reflet d'un prélevement accru de l'azote par les arbres.

[Traduit par le journal]

Introduction

Spacing² and thinning treatments in young dense northern coniferous forest stands are known to increase basal area growth (Eversole 1955; Alexander 1960; Sjolte-Jørgensen 1967) and nitrogen concentrations in the foliage (Weetman 1968, 1971). Thinning results in heavier snow accumulation (Goodell 1952; Braathe 1957) and earlier thawing of frozen soils (Ångström 1936), thus prolonging the period of active decomposition and root activity in the forest floor. Spacing and thinning increase the

summer temperatures in the forest floor (Ångström 1936; Strand 1968; Timmer and Weetman 1968) and may also increase the soil moisture content because there is less competition for moisture (Orr 1968).

Less is known about changes in nutrient distribution in the forest floor profile following spacing and thinning in forest stands. Boyer and Fahnestock (1966), Dickerson (1972), and Wollum and Schubert (1975) observed decreases in the weights of forest floor organic matter in spaced stands, presumably owing to an acceleration of the decomposition process. It has been theorized that this could result in increased availability of nutrient elements (Yamamoto and Sanada 1970; Robarge *et al.* 1968). In contrast, Weetman (1965) noticed an inverse relationship between weight loss of organic matter contained in litterbags and thinning treatment in black spruce (*Picea mariana* (Mill.) B.S.P.) stands in Quebec, which he attributed to a more favorable moisture regime in the forest floor in the unthinned stand. This might lead to adverse effects on the nutrient regime in the forest floor. Research is needed

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²"Spacing" is a commonly used term in eastern Canada to describe a type of silvicultural treatment in dense young stands, not past the sapling stage, in which less desirable trees are cut so as to leave crop trees at a predetermined and more or less equal distance apart (i.e., at a desired spacing). The operation is referred to as a "spacing treatment" and the resultant stand as a "spaced stand." This treatment is distinguished from "thinning," which refers to similar work in older stands, and from "cleaning," which is concerned primarily with the removal of unwanted tree species and shrub growth in young stands and which does not necessarily result in an equal spacing of the remaining crop trees.

to quantify the effects of spacing and thinning on changes in decomposition rates and associated changes in forest floor biomass and nutrient regimes for different forest ecosystems.

The study reported in this paper was initiated in the fall of 1973 on the Cape Breton Highlands, Nova Scotia. The main objectives were to investigate changes in (1) carbon and nitrogen mineralization and (2) temperature of the forest floor litter (L) layer following spacing treatment in a young balsam fir (*Abies balsamea* (L.) Mill.) stand.

Study Area

The general study area is in Victoria County, Nova Scotia ($46^{\circ}09'N$ and $60^{\circ}49'W$), at an elevation of approximately 400 m. The area is within the Cape Breton Highland District of the Gaspé–Cape Breton Ecoregion (Loucks 1962). The climate is humid and temperate, with a mean annual temperature and precipitation of about $6^{\circ}C$ and 125 cm, respectively. One-third of the precipitation falls during the growing season and the frost-free period is about 90 days (Bailey and Mailman 1972).

The Cape Breton Highlands are covered with an almost pure balsam fir forest of which large areas were clear-cut in the mid-1950's. On most of the cutovers, dense stands (up to 80 000 stems/ha) of balsam fir have become established mostly from advance regeneration. Scattered white birch (*Betula papyrifera* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), and sugar maple (*Acer saccharum* Marsh.) are also found. In 1971, several of these dense balsam fir stands were operationally spaced to about 2.4×2.4 m (8×8 ft), 1642 stems/ha.

The ground vegetation in the spaced stands is dominated by bunchberry (*Cornus canadensis* L.). Very few species are present in the untreated stands, with *Oxalis montana* Raf. and *Dicranum* spp. being the most abundant.

The thickness of the combined L + F + H layer ranges from 25 to 70 mm. The soil is a weakly developed humo-ferric podzol with a thin leached layer (Ae horizon) occurring locally. The B horizon is about 40 cm thick and the parent material is a till derived from igneous rock of gabbro, diorite, and granitic types together with metamorphosed sandstones.

Materials and Methods

Within the general study area, two 0.025-ha plots (15.8×15.8 m) were established; one in a 22-year-old spaced stand, the other in a 22-year-old untreated stand (control) (Table 1). Each plot was divided by a grid system into 36 equal-sized subplots.

Temperature Measurements

The temperature in the L layer was recorded in the spaced and control plots by a battery operated Sumner long-term temperature recorder (Timmer and Weetman 1968). The temperature probes, one in each plot, were placed horizontally in the L layer about 2 cm below the surface and remained there from 11 November 1973 to 10 June 1975. The probe in the spaced plot was carefully placed so as to represent the average temperature conditions.

Carbon Dioxide Evolution

Twelve subplots were randomly chosen in both the spaced and control plots for respiration measurements. The respiration chambers used in this study (Piene and Van Cleve 1976) were made of ABS plumbing pipe with a closed bottom piece and a tight-fitting lid. They were placed in 6-cm-deep holes, where they remained during the 1974 and 1975 summer seasons.

Samples from the forest floor L layer were collected, with a pair of forceps, from undisturbed sampling areas (30×30 cm) located in each of the 36 subplots in both the spaced and control plots. The respiration samples consisted solely of balsam fir needles in an early stage of decomposition; these were easily separated from the forest floor F layer (L-layer material from under slash piles resulting from the spacing operation was not used in respiration studies). About 5 g of this material was placed in a stainless-steel screen basket inside the chamber. The top of the chamber was firmly attached and sealed with petroleum jelly. One thermistor probe was introduced into the respiring sample through the top of the chamber and one was placed outside the chamber in the L layer to determine if the temperature recorded inside the chamber coincided with the temperature outside. Both temperatures were recorded at 10-min intervals using a 20-channel Grant recorder. On sunny days, it was necessary to cover the respiration chambers with aluminum foil to avoid excessive heating.

With a syringe, 8 ml 1 N KOH was introduced through the serum bottle stopper into the KOH reservoir. After 4–5 h (Piene and Van Cleve 1976), 2 ml KOH was withdrawn from the chamber and emptied into a 50-ml Erlenmeyer flask. About 3 ml 3 N BaCl₂ was added, and the flasks and the respiration samples were immediately brought to the laboratory for determinations of the amount of CO₂ evolved and the content of extractable ammonium nitrogen.

Measurements of CO₂ evolution were made on eight occasions. The first three respiration measurements (13 and 26 July, 9 August 1974) were made on composite samples, one from the 12 subplots in the spaced plot and the other from the 12 subplots in the control plot. The last three respiration measurements in 1974 and the two measurements in the spring of 1975 were made on separate samples taken from each subplot, within the two experimental plots.

Collection of L-layer Biomass, Litter Fall, and Foliage

A total of 36 composite samples (each consisting of three subsamples) of the L layer was collected 1 September 1974 from the two study plots using a 6.3-cm-diameter core sampler. The samples were brought to the laboratory where twigs, cone shells, and mosses were separated and discarded. The samples were dried for 48 h at $65^{\circ}C$ and weighed. Also, five composite samples were collected from the control and spaced plots for analysis of percentage carbon.

Litter fall was collected in the control and spaced plots during the 1974–1975 season using five litter screens (0.6×0.6 m) in each stand. The litter was collected each month

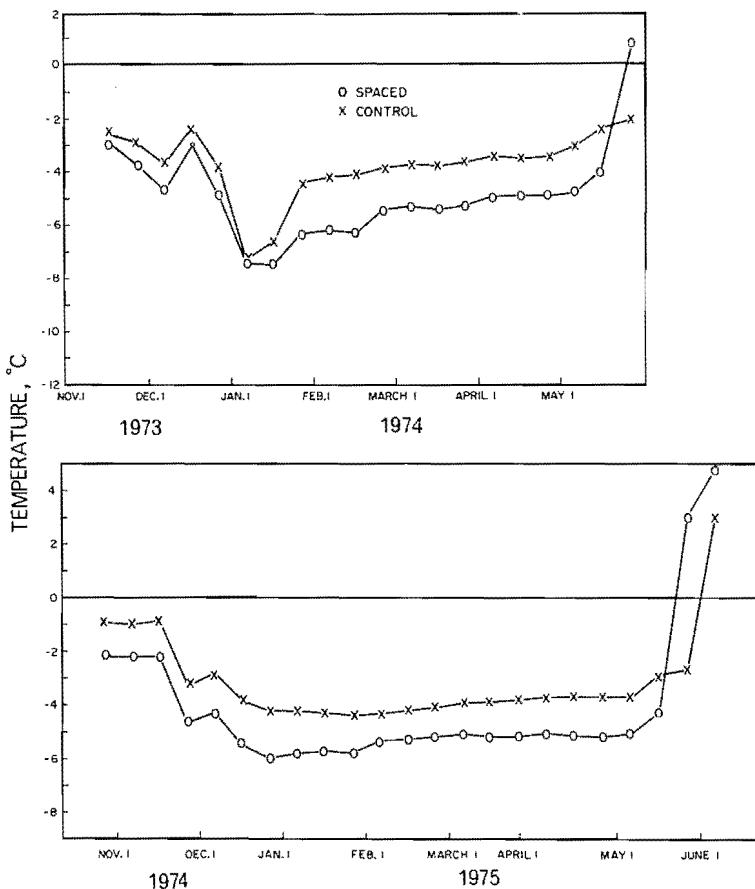


FIG. 1. Average 10-day temperatures in the L layer 2 cm below the surface of the spaced and control plots for the winters of 1973-1974 and 1974-1975.

(except in the winter) and brought to the laboratory where the twigs were separated and discarded. The samples were then dried for 48 h at 60°C and weighed.

After the 1973 and 1974 growing seasons, 10 dominant and codominant trees were selected in the spaced and the control plots, and samples of current-year foliage were taken from the fourth whorl from the terminal bud. The samples were taken to the laboratory where the needles from each tree were separated from the branches and pooled. From each pooled sample, 900 needles were counted in portions of 300. The portions were dried for 48 h at 60°C and then weighed. Subsamples were taken from each collection for total nitrogen determinations.

In addition, at the end of the 1974 growing season, increment cores from 20 dominant trees in both the spaced and control plots were taken at the diameter at breast height (DBH) and measured to determine increases in basal area (BA) growth as a result of spacing. The ring widths were measured to the nearest 0.01 mm on an Addo-X ring-width measuring machine.

Analytical Methods

The amounts of CO_2 absorbed by the KOH solution were determined by titration with standard acid.

The ammonium nitrogen in the litter from the respiration chambers was extracted using 2 N KCl and this was analyzed by alkali distillation.

Total nitrogen contents of the foliage were determined by standard Kjeldahl methods. Carbon contents of the L layers, following removal of twigs, were determined on ground samples using a Leco automatic carbon analyzer (Tabatabai and Bremner 1970).

Results and Discussion

Forest Floor Temperatures

Figure 1 shows the temperature fluctuations in the forest floor L layer during the winters of 1973-1974 and 1974-1975.

The 10-day average temperature recordings indicated a pronounced frost penetration (especially in 1973) through late December and early January. After 1 February, additional frost penetration ceased and the thermal environment under the snow was almost stable.

Snow depth measurements in the spaced and control plots in 1974 and 1975 indicated that snow layers, approximately 50 cm thick, in November and December permitted deep frost penetration particularly in the spaced plot. The thick snow layer (1.1

to 1.3 m) present after 1 February prevented further cooling of the L layer and may have insulated the forest floor from the air, thus giving the spaced plot lower temperature recordings in the L layer throughout the winter (Fig. 1). Timmer and Weetman (1968) studied humus layer temperatures and snow-cover conditions under upland black spruce in northern Quebec. They concluded that although little temperature difference was detected between thinned and unthinned stands in the winter, a constant lower temperature was detected in a clear-cut stand. Pierce *et al.* (1958) observed deeper frost penetration under snow in open lands as compared with forest land, averaging 13 and 6 cm, respectively. However, Weitzman and Bay (1963) noted a reduction in frost depth under snow in spaced stands, presumably because the greater snow accumulation was a better insulator.

A slight warming trend occurred after 1 February in both experimental plots; this was especially pronounced in 1974. The radiation absorbed at the snow surface during the day would not be transmitted to the L layer because of the thick snow cover prevailing during the winter. Rather, the warmer temperatures recorded in both the spaced and control plots, especially in February, March, and April, could be caused by deep-stored heat (Federer 1965). In May, the thermal regime in the L layer is probably influenced by warm air temperatures, since part of the insulating snow cover has thawed. The critical snow depth at which the air temperature has no effect on the thermal regimes in the L layer (Hart and Lull 1963) is difficult to estimate as few snow depth measurements were recorded. However, the measurements showed that temperatures as low as -7.5°C occurred in the spaced plot under a snow cover of 50 cm. As also noted by Timmer and Weetman (1968), the critical snow depth of 45 cm (Hart and Lull 1963) at which the air temperature has been reported to have no effect on the thermal regime in the L layer may be too low for our northern coniferous forested areas.

From these results, it would appear that the soil temperatures in the fall before a thick snow cover accumulates would largely determine the prevailing winter soil temperature regime. This means that if very little frost had penetrated the soil before the arrival of a heavy snow cover, temperatures around 0°C may be recorded throughout the winter. In contrast, as in this study, a fall with frequent severe frosts may result in humus temperatures as low as -7.5°C .

The frozen forest floor L layer in the spaced plot thawed 20 days earlier in 1974 and 12 days earlier

in 1975 than in the control. This is in agreement with Ångström (1936) and Yli-Vakkuri (1960) who studied thinned spruce stands in Scandinavia.

According to Jablanczy (1965), the threshold temperature for root activity in white spruce is approximately 7°C . Assuming that this temperature is the same for balsam fir, the temperature measurements in the L layer indicated that this threshold temperature was reached much earlier in the F and H layers, the major rooting zone for balsam fir (Dammann 1971), in the spaced plot than in the control. This would reduce the lag period in the spring between the initiation of shoot and root growth in the spaced plot.

The total weekly accumulated degree hours was about 20% higher in the L layer in the spaced plot than in the control (Fig. 2). This difference was most pronounced at the beginning of the summer because the protecting forest cover slowed down the temperature increase in the control plot.

Changes in Carbon and Nitrogen Mineralization

Significant differences in temperature between the inside and outside of the respiration chambers occurred only on 26 July for both the spaced ($P = <0.05$) and control ($P = <0.01$) plots (differences were 2.2°C and 1°C , respectively), and on 9 August for the control ($P = <0.001$) (the difference was only 1°C) plot. Thus, the temperature measured inside the chambers during respiration measurements closely represented the actual temperatures in the L layer outside the chambers.

At each measurement, evolved CO_2 and extractable ammonium nitrogen were significantly higher ($P = <0.01$) in the spaced plot than in the control (Fig. 3) except on 17 August for CO_2 and on 17 August and 8 September for ammonium nitrogen. These observations suggest that an increase in organic matter decomposition, as indicated by CO_2 evolution, has occurred in the spaced plot and that this is associated with an increase in mineral nitrogen levels in the forest floor L layer (Fig. 4). Although the biomass of the L layer in the control plot in 1971 (time of spacing) was not recorded, the measurements in 1974 indicated that a substantial decrease in L-layer biomass in the spaced plot had occurred (Table 1). It should be pointed out that this decrease in forest floor biomass is also partly due to reduced litter deposition and leaching losses in the spaced plot. Positive correlations between CO_2 evolution and weight loss of organic matter have been observed by Witkamp (1966) and by Ivarson and Sowden (1959).

An increase in mineral nitrogen in a spaced stand has also been noted by Popovic (1971) who incu-

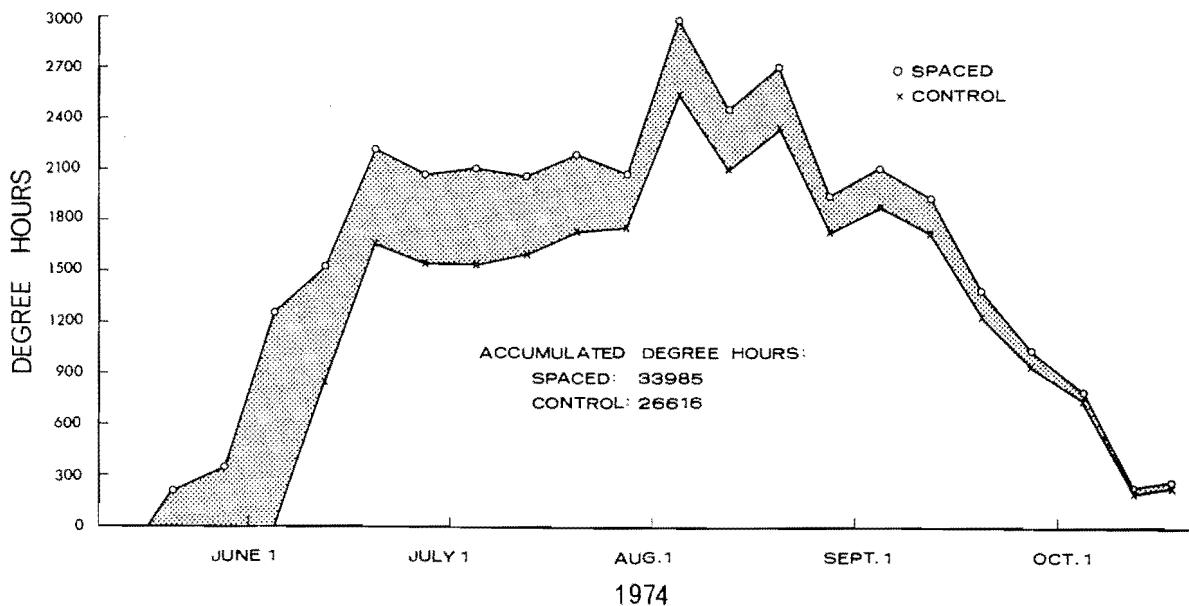


FIG. 2. Weekly accumulated degree hours above 0°C in the L layer of the spaced and control plot (1974).

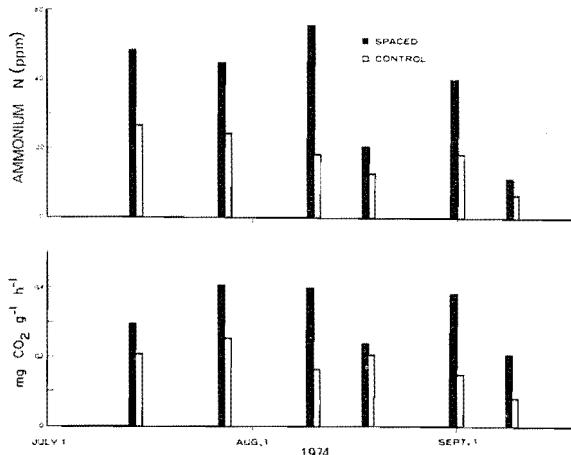


FIG. 3. Carbon mineralization and extractable ammonium nitrogen from L-layer material in spaced and control plots (summer 1974). Each bar represents an average of 12 determinations.

bated forest floor samples collected in thinned spruce stands in Sweden.

Studies have shown that high rates of CO_2 evolution from organic matter are associated with large microbial populations (Witkamp 1963), and as a result, immobilization of elements is positively correlated with CO_2 evolution. Because immobilized elements are released upon death of the microorganism tissue, a similar relationship exists between CO_2 evolution and remineralization. Depending on the decomposability of the substrate, a similar relation-

ship may exist between CO_2 evolution and net mineralization of elements. Incubation experiments with different types of raw humus have clearly shown that during periods of high gross mineralization induced by increasing the temperature, low net accumulation of nitrogen has occurred (Zöttl 1960). It is interesting to compare these observations with those from the present study. These indicate that with an increase in temperature, and thus CO_2 evolution, an increase in mineral nitrogen levels occurs (Fig. 4). The explanation for this may be that the organic matter in the field is exposed to constantly changing environmental conditions, thus inducing repeated cycles of microbial bloom followed by microbial collapse and release of minerals. This is in contrast with the stable environmental conditions in the laboratory.

The variability in CO_2 evolution rates observed in the present study (Fig. 4) reflects the effects of the different temperatures, moisture contents, and available substrates on the activity of the microorganisms in the respiration samples. Evolution of CO_2 from incubated litter is known to be relatively unaffected by a moisture content above about 100% by dry weight (Wiant 1967; Piene and Van Cleve 1976). As moisture content fell below this value only on 9 August, temperature would be expected to be the main factor controlling variations in carbon mineralization rates in the forest floor L layer (Fig. 5). In fact, Fig. 4 shows that a close curvilinear relationship existed between temperature measured outside the

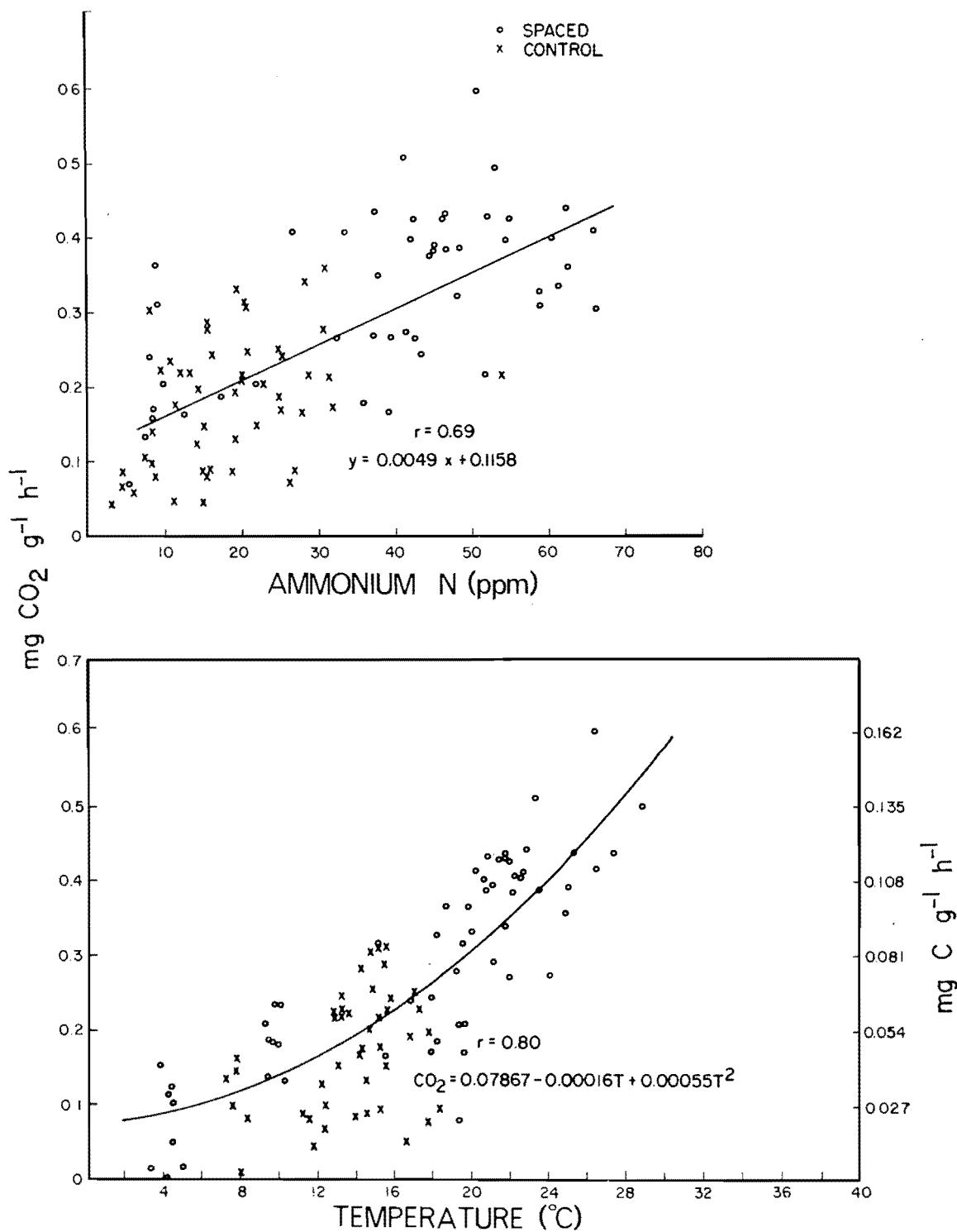


FIG. 4. The relationship between CO_2 evolution and extractable ammonium nitrogen from forest floor L layer (upper) and carbon mineralization and temperature (lower) (summer 1974). Each point represents one determination from a respiration sample.

TABLE 1. Mensurational, biomass, litter fall, and organic carbon measurements from the different balsam fir stands, 1974

Plot	Stems/ha	BA/ha, m ²	Age	Average DBH, cm	Average height, m	Biomass, kg/ha			Litter fall, ^a kg/ha	Organic carbon, %
						L	F + H	Total		
1 (spaced)	1642	12.1	22	10.8	6.0	6335 ± 879 ^b	35387 ± 3214	41722	919 ± 396	52.2 ± 1.0
2 (control)	19000	37.3	22	4.6	6.2	11375 ± 1220	36276 ± 2814	47651	2229 ± 362	51.8 ± 1.5

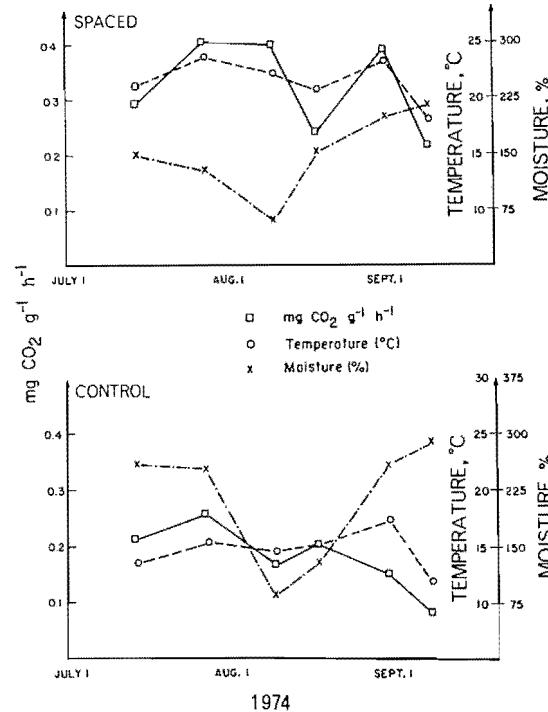
^aCollecting season of 1974-1975.^bStandard error (95% confidence interval).

FIG. 5. Seasonal trends in respiration, temperature, and moisture content in L-layer material (1974). Each point represents an average of 12 determinations.

respiration chambers and carbon mineralization rate.

Similar relationships have been obtained by Reiners (1968), Kucera and Kirkham (1971), and Edwards (1975) using the "inverted box" method which measures total forest floor respiration including that originating from roots.

Previous investigations have generally emphasized the measurement of carbon dioxide from the total forest floor profile, and only limited information is available on respiration rates from discrete forest floor layers. Incubation studies by Roberge (1971), using L-layer samples from a black spruce forest, and by Kowal (1969), using pine needles, indicate slightly lower respiration rates than those obtained in the present study for comparable temperatures and moistures. In contrast, Van Cleve and Sprague

(1971) reported higher respiration rates for birch and aspen L layers incubated in the laboratory. This probably reflects higher contents of available nutrients for the microorganisms in the birch and aspen litter than in balsam fir needles (Melin 1930).

Based on measurements of litter fall (Table 1) and temperature (Fig. 2) in the spaced and control plots and the relationship between temperature and carbon mineralization rates (Fig. 4), weight loss of the forest floor L layer was predicted for the control plot in 1974 and for the spaced plot from 1971 to 1974 (weight loss owing to leaching was not considered), using the equation:

$$A = (B + L) - [(B + L) \times R \times Q],$$

where for a certain time period, A = the biomass present at the end, B = the biomass present at the beginning, L = litter fall reaching the forest floor, R = the respiration rate corresponding to the average temperature, and Q = a factor (0.524) to convert the amount of CO_2 evolved to the equivalent amount of organic matter using an average percentage carbon of 52.0, determined from the spaced and control plots in the present study (Table 1).

Changes in forest floor L-layer biomass were calculated using a computer program for each 2 h in the estimation period. The litter fall reaching the forest floor was estimated by dividing the monthly litter collection into equal parts.

(I) Control Plot, 1974

Based on the prediction procedure, the weight loss in the control plot for 1974 amounted to 2180 kg/ha, which approximates the annual litter fall of 2229 kg/ha. It would be of interest to examine further if the total yearly input of carbon (including twigs) balances the carbon lost as CO_2 from the total forest floor, suggesting that an equilibrium level would be reached early in stand development (Turner and Long 1975). This is indicated from measurements of litter fall and forest floor biomass in the control and an adjacent 38-year-old unspaced stand (Piene, unpublished data), which show approximately the same values.

TABLE 2. Changes in percentage nitrogen, weight of balsam fir needles in the 2nd (1973) and 3rd (1974) years after spacing, and basal area increment before and after spacing

Parameter determined	Year	Treatment	Mean \pm SE ^a
Needle weight (g/1000 needles)	1973	Control	4.5909 \pm 0.3386
		Spaced	5.2895 \pm 0.5157
	1974	Control	4.2713 \pm 0.2348
		Spaced	5.5103 \pm 0.3645
Percentage foliar nitrogen	1973	Control	1.42 \pm 0.07
		Spaced	1.63 \pm 0.13
	1974	Control	1.38 \pm 0.06
		Spaced	1.55 \pm 0.08
ABI ^b (cm ² /tree)	Before spacing	1969-1971 (average value)	2.88 \pm 0.95
			4.19 \pm 0.68
	After spacing	1972	2.78 \pm 0.77
			5.51 \pm 1.41
		1973	3.18 \pm 0.88
			8.07 \pm 1.85
		1974	3.40 \pm 1.16
			9.86 \pm 1.54

^aStandard error (95% confidence interval).^bAnnual basal area increment.

(2) Spaced Plot, 1971-1974

Assuming that the biomass of the forest floor L layer reached an equilibrium level before 1971 (time of spacing), the biomass in the spaced plot in the fall of 1974 was predicted to be 7643 kg/ha compared with an estimated 6335 kg/ha (Table 1). This represents total predicted and estimated weight losses since spacing treatment of 6490 kg/ha and 7797 kg/ha, respectively, which is a difference of 1307 kg/ha. This prediction is based on the assumptions that (1) the litter fall in the first 3 years after spacing did not change significantly (Reukema 1964) and was the same as that in the 1974-1975 collecting season and (2) the temperature measured in 1974 in the forest floor layer was similar to temperatures for the 1972 and 1973 summer seasons. This is indicated from air temperatures measured in the vicinity of the research area³ which show a close resemblance between the 1972, 1973, and 1974 temperatures.

Although the prediction discussed above has limited value because of the assumptions used, it does show the importance of temperature in controlling the microbial breakdown of organic matter for this forest ecosystem. The prediction may also suggest that carbon dioxide evolution could potentially be useful in predicting weight changes in thin forest floor L layers where aerobic conditions prevail and root respiration is excluded.

³Unpublished document, Canadian Forestry Service, Fredericton, N.B.

Growth Response

Spacing treatment was associated with significant increases in foliar nitrogen concentrations and needle weights in both the 2nd and 3rd year after spacing (Table 2), thus reflecting increased nitrogen uptake by the trees. These results show that the balsam fir stand had been deficient in available nitrogen and the trees responded to spacing by increased basal area growth. This is in agreement with the observations discussed previously where spacing contributed to an increase in the mineral nitrogen supply in the forest floor. They also agree with the well established observations of general nitrogen deficiency in boreal forests associated with competition for available nitrogen in raw humus soils (Weetman and Algar 1974).

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